Renewable Energy Storage and Sustainable Design of Hybrid Energy Powered Ships: A Case Study

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Abstract

With rapidly increasing consumption of energy, shipping industry has imposed a huge burden on the marine environment. It is a general trend to increase the use of renewable energy on ships to improve the ship sustainability. This article summarized the current development and application of solar energy, wind energy and fuel cell in ship power systems. Furthermore, in order to investigate the advantages of sustainable design for the ships, for the first time, a

hybrid PV, wind and fuel cell energy system was established for an oil tanker, and the economic and environmental analyses of the hybrid system were performed. The analysis results demonstrate that the optimal hybrid energy system can reduce 151,467kg emission of CO_2 and provide 2.92% electricity for the ship gird per year.

Keywords: Renewable energy; Energy storage technology; Ship power sustainability; Economic and environmental analysis

1. Introduction

In contemporary society, various industries need more and more energy to meet their growing demands; nevertheless, the consumption of non-renewable energy causes great harm to the environment [1]. The large-scale use of non-renewable energy will not only lead to the inevitably shortage of resources in the future, but also gives rise to a series of international conflicts and problems. It is an urgent task to reduce the dependence of fossil fuel by vigorously extending the using of renewable energy, and it is of great importance to the future of all human beings. Countries around the world are gradually aware of this problem, with so many efforts made for the development and utilization of renewable energy [2-5]. According to the date of IRENA, we have more than 584GW of solar installation capacity and 622GW of wind power installation now. Researches and utilizations of renewable energy are getting much more and further. The construction and operation cost of renewable energy is lower on land and therefore most of the renewable energy projects are located on land or offshore. Whereas the oceans make up more than 70 percent of the earth and hold an incredible amount of untapped potential for developing renewable resource such as solar and wind. Even so, the energy of Marine engineering platforms such as ships and offshore platforms mainly supply by non-renewable energy regardless of the advantage from the ocean [6]. Nowadays, renewable energy utilization technologies such as solar energy, offshore wind power and fuel cell are increasing rapidly, the promotion and application of marine renewable energy has become an inevitable trend especially on ships [7-10].

As the main way for global trade transportation, shipping caused inevitably huge pollution, although the MARPOL Convention has strict regulations on pollution from ships [11]. Using the renewable energy to replace the fossil fuel is the most effective method to change this exigent

73 situation from the root.

74 Solar radiation is the main energy source on the surface of earth with a whopping $1.73\times$

75 10^{17} J of energy per second. It can provide a huge amount of energy for ships with solar

76 installations [12]. Offshore wind turbine has a long history of development and it is very suitable

77 for the power supply to the port which positions are fixed [13-14]. At the same time, using batteries

78 to overcome the intermittent and unstable nature of solar and wind power is an ordinary method.

79 The excess electricity supplies to the electrolyzer to produce hydrogen for fuel cell. All the

80 mentioned renewable energy with addition of diesel generator constitute the ship electricity

81 power and this kind of hybrid renewable energy system is definitely environmentally friendly

82 with so much reduction of emission.

83 This article summarizes the general development situation of the renewable energy

84 technologies and the applications in the ocean. The feasibility of applying the above renewable

85 energy technologies to ships is illustrated and the economic benefits are discussed. The

86 contributions and innovations of this review include the following points.

87 (1) For the first time, the practical applications of clean energy for ships are summarized.

88 (2) Economic analysis of a hybrid PV, wind and fuel cell energy system is performed to

89 illustrate potentials of hybrid power ships.

90 **2. Renewable energy applications**

91 According to Renewable Capacity Statistics 2021, in the end of 2020, renewable

92 generation capacity amounted to 2799 GW all around the world [12-17]. Solar and wind accounted

93 for 25.5% (714 GW) and 26.1% (733GW) respectively. Renewable generation capacity

94 increased by 261 GW in 2020 and 10.3% as compared with last year. Solar energy and wind

95 energy increased by 127 GW and 111 GW respectively. Solar and wind led the capacity

96 expansion with 91% of new capacity in 2020. In view of this, solar energy and wind power are

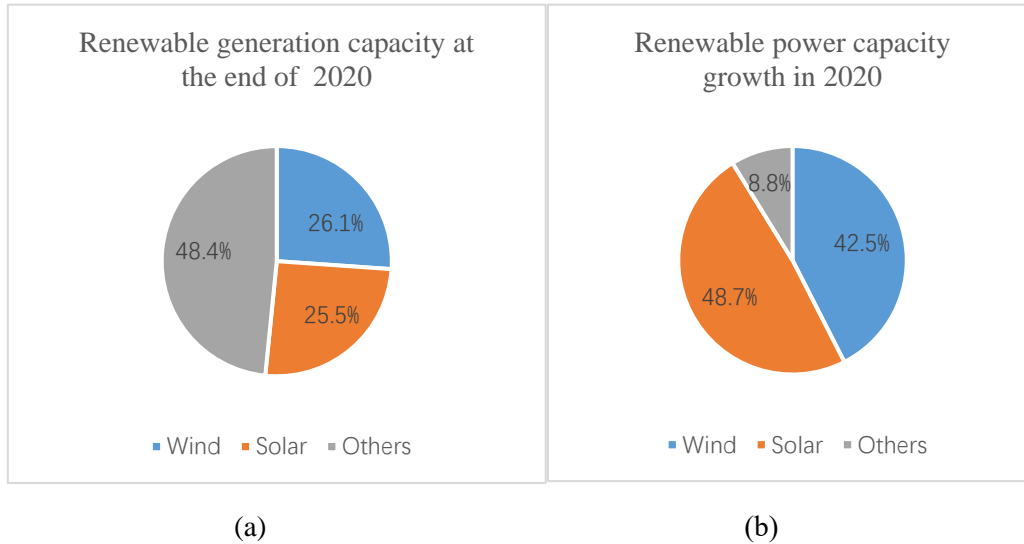97 mature technologies with great utilization prospects [18-20].

Renewable generation capacity at the end of 2020 — (a)

Renewable power capacity growth in 2020 — (b)

98
99   (a)   (b)

100   Fig 1 Renewable electricity generation and capacity growth

101   2.1 Solar energy applications

102   The manufacturing cost of solar panels has been drastically reduced for the last 10 years.

103   With the support of various policies, solar energy has been widely used and therefore solar

104   photovoltaic (PV) has become one of the fastest developing new energy technologies.

105   According to the dates from IRENA, the capacity of solar PV increased from 72 GW to 714

106   GW in the decade between 2011 and 2020 [12-17]. The rapid growth of solar PV is closely related

107   to the substantial reduction in its cost. At present, the PV utilization cost in the world is

108   generally lower than 0.2 USD/kWh and it will definitely get much lower with the PV industry

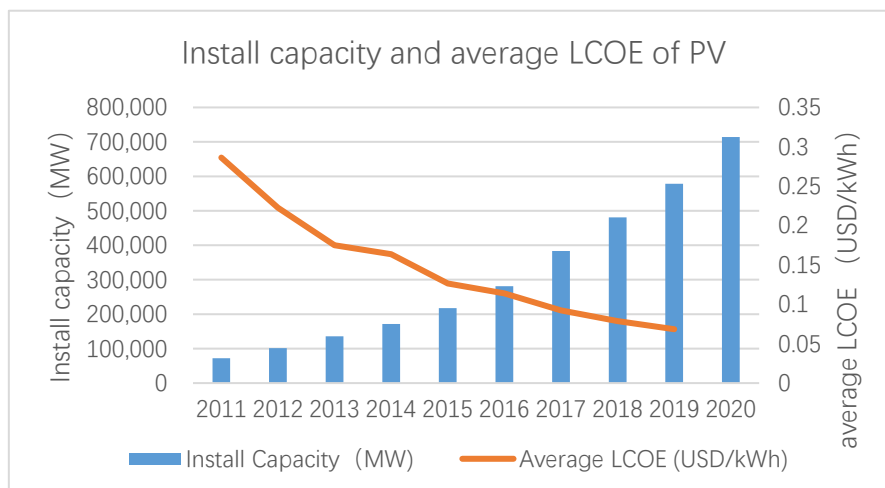109   developing.

110
111   Fig 2 Install capacity and LCOE of PV

112   The solar radiation absorption efficiency of photovoltaic power generation is only about

113   15-20%. In comparison, solar thermal utilization has higher efficiency. In recent years, solar

114   thermal utilization is also a hot research topic and photovoltaic–thermal system attracted the

115   attention of many scholars. Relevant concepts and experimental studies about PVT system first

116   appeared in the 1970s. After half a century of development, the system has gradually become

117   mature. PVT collects heat while generating electricity, reducing the temperature of the collector

118   and improving its overall efficiency. Mainstream solar photovoltaic thermal systems fall into

119   two main categories: Flat-plate PV/T and concentrator type PV/T. Normally the working

120   medium of PV/T systems is air or water, but there are also some special systems based on Nano

121   fluid, PCM and refrigerant [21].

122   The research on the experiment and simulation model of the plate solar collector has been

123   very complete and advanced. Current research is mainly focused on using new materials to

124   improve system efficiency [22], analyzing the main structural factors and performance

125   parameters that affect the efficiency of flat-panel PV/T system, and exploring the possibility of

126   effectively using PV/T system to hybrid energy systems [23]. Fig.3 shows the working principle

127   of the flat-panel solar PV thermal system, which can be divided into liquid-type PV/T system,

128   air-type PV/T system and Bi-fluid type PV/T system according to the different working fluids

129   [24]. The efficiency of air-type PV/T system is lower than other types but its structure is the

130   simplest and it gets a lower installation cost. Liquid PV/T systems have better heat transfer

131   capacity, especially with phase change materials and Nano fluids, but their structure is more

132   complex and the cost is higher. Bi-fluid type PV/T system is a compromise between the two

133   systems. In general, each system has its own advantages and disadvantages, and needs to

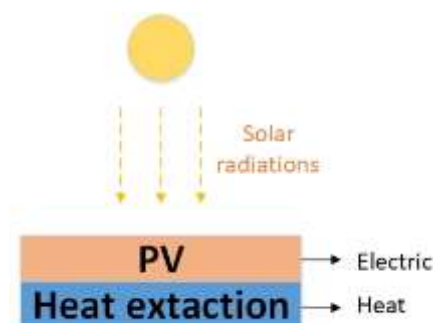134   consider the application environment to choose the suitable system.

135

136   Fig 3 Flat-plate PV/T system

137   The principle of centralized PV/T system is to enhance the received solar radiation

138   intensity through the reflector while reducing the receiving area. In this way, the efficiency of

139 the system is increased while the cost of the system can be reduced. Fig. 4 shows the working

140 principle of the centralized PV/T system. The power generation efficiency of PV is improved

141 by increasing the radiation intensity, while the collector module absorbs the concentrated light

142 as well as a large amount of heat generated by the PV module due to its high efficiency operation.

143 High temperature has a negative impact on PV and makes the generation efficiency have a

144 certain loss. As a result, the heat collector module is the core-working component of the system.

145 Making the system run efficiently and safely at high temperature is the difficulty of its

146 application. The centralized photovoltaic thermal system can operate stably at 170 °C [25], but

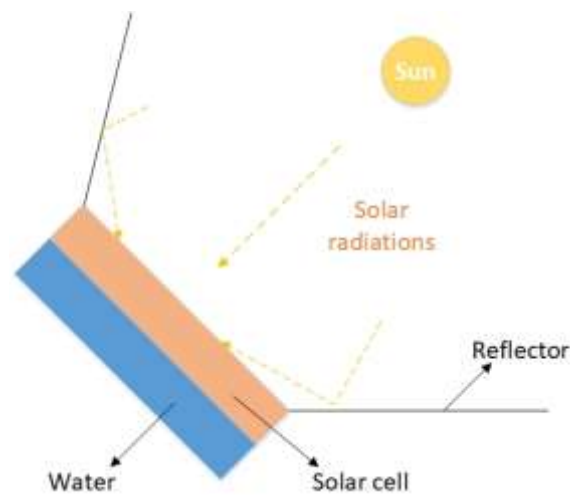147 further researches are still needed.

148

149 Fig 4 Concentrator type PV/T system

150 In addition, hydrogen is an expensive fuel due to the high cost of hydrogen production by

151 electrolysis. Solar as one of the most developed renewable energy sources, hydrogen production

152 with solar energy is undoubtedly one of the most promising methods. Hydrogen production by

153 solar mainly includes photoelectric solution, Photovoltaic (PV), photoelectric chemistry,

154 thermal chemistry and artificial photosynthesis [26]. PV hydrogen production is one of the most

155 economical methods. This technology is mature for application after about 50 years'

156 development [27] and the efficiency can reach 25% [28]. Moreover, different from other solar

157 energy utilization methods, PV hydrogen production takes no account of the disadvantages of

158 fluctuations and intermittences by transforming the solar into a stable resource.

159 2.2   Wind energy applications

160 Wind power is one of the more easily available renewable energy sources, with around

161   20,000 GW available worldwide; nearly eight or nine times the current global total. Wind power

162   is also one of the fastest developing renewable energy sources. Under the development of

163   related research and the promotion of new energy policies in various countries, the cost of wind

164   power is getting much lower, and the scale is getting much larger. Over the past two decades,

165   the installed capacity of wind power has increased more than seventy times. Installed capacity

166   has increased by about 442GW, from 180GW in 2010 to 622GW in 2020.Actual electricity

167   generation increased nearly fourfold from 342,831 GWH in 2010 to 1,262,914 GWH in 2019.

168   Currently, the utilization cost of wind power in various countries is generally lower than

169   0.1USD /kWh.

170

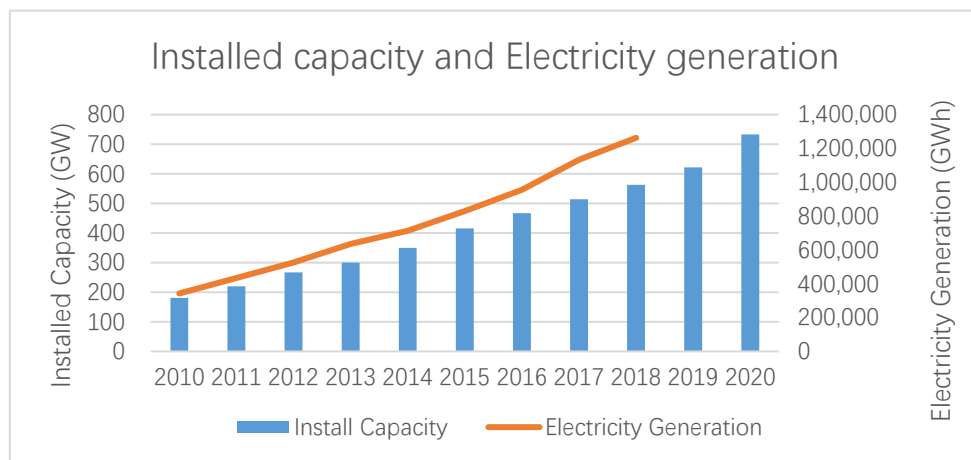171   Fig 5 Installed capacity and Electricity generation

172   Wind power generation technology has been widely used, whether in the land or the sea.

173   The offshore turbine has a great potential because of the advantages of continuity, steadiness,

174   high speed, large capacity and far away from living quarters. As the main tool of wind energy

175   utilization, wind turbine has a long history of development. In March 2017, DONG Energy

176   decided to decommission the Vindeby offshore wind farm, which is the world's first offshore

177   wind farm installed in 1991 and worked for about 25 years. In 2009, the first large deep-water

178   floating fan was built at the Hywind wind field in Norway, with a power of 2.3MW and standing

179   at 220 meters deep. Currently, only the United Kingdom, Germany, Denmark, the Netherlands

180   and China have offshore wind farms with a capacity of more than 400MW. Table 1 shows the

181   countries with the largest installed offshore wind power capacity in recent years. The largest

182   offshore wind farm is Hornsea 1 in the UK, which has a capacity of 1,218MW and turbines

183   from 3.6 to 8 MW rated power [29].

Table 1 Installed offshore wind power capacity (WM) [6]

Year	United Kingdom	Germany	China	Denmark	Belgium
2016	5156	4108	1627	1271	712
2017	6651	5411	2788	1268	877
2018	7963	6380	4588	1329	1186
2019	9723	7493	6838	1703	1556

184   Fig 6 shows the current three main types of offshore wind turbines, which are divided into

185 horizontal axis and vertical axis according to the type of shaft. The most widely used is the

186 horizontal axis wind turbine (HAWT). The main rotor shaft and generator of the HAWT (Fig

187 6a) are located at the top of the wind turbine. HAWT has to be angled towards the direction of

188 the wind, so it is always equipped with wind direction sensors to help adjust the direction of

189 the wind turbine. Currently, the largest HAWT in the world is the Haliade-X wind turbine,

190 which is rated at up to 12 MW [30]. The main rotor axis of vertical axis wind turbine (VAWT)

191 (Fig 6b) is perpendicular to the wind direction. This structure makes for the generator and other

192 equipment can be placed in the base of the turbine, reducing the difficulty of installation and

193 maintenance and increasing the safety of the system. The VAWT has no requirements on the

194 wind direction but is less efficient than HAWT and producing much less power at the same

195 wind. The cross-axis wind turbine (CAWT) (Fig 6c) is actually an improvement of VAWT [31].

196 It combines the strengths of HAWT and VAWT while overcoming their weaknesses. Like

197 VAWT, CAWT occupies much less space than HAWT, and the blade swept area of CAWT is

198 much larger than that of VAWT, so it gets a higher conversion rate of wind energy [32]. CAWT

199 is still in the exploratory stage and has a long way to go before application.

200

201   a   b   c

202   Fig 6 HAWT (a); VAWT (b) [33]; CAWT (c)

203   Offshore wind power generation is very important for reducing carbon dioxide emissions

204   and improving the global environment. However, due to the nature of wind resources, wind

205   power generation is not particularly stable, and there will be excess wind power that needs to

206   be discarded in the generation process resulting in the waste of wind resources [34]. Using wind

207   power to produce hydrogen and increasing the on-site consumption of wind power plants is one

208   of the important ways to reduce wind curtailment [35]. This not only ensures the safety and

209   stability of wind power plants and power grids, but also avoids wasting resources. Hydrogen

210   production by wind power generation in ports can also provide a large amount of hydrogen

211   sources for ships, which is conducive to promoting the renewable development of ship energy

212   systems.

213   People began to explore the possibility of hydrogen production from wind power at the

214   beginning of this century. Kassem [36] analyzed the feasibility of hydrogen production by wind

215   power in 2003, and demonstrated that this method is of great research value and is an effective

216   way for hydrogen production using renewable energy. Bartels [37] made a comprehensive

217   economic analysis of hydrogen production from wind power and analyzed the feasibility from

218   an economic perspective. After the hydrogen production from wind power generation has been

219   gradually recognized, the related specific topics have been widely studied. Takahashi et al. [38]

220   proposed a coordinated control method for hydrogen production from wind power, which

221   effectively reduces the impact of wind fluctuations on the power system. Belmokhtar [39]

222   proposed an optimized control method based on fuzzy logic based on the technical principle of

223   hydrogen production by wind power, which effectively improved the efficiency of the system.

224   At the national level, the United States, the European Union and China all started a series of

225   projects to produce hydrogen from wind power. The United States was the first to carry out

226   wind power generation hydrogen production projects, but it did not receive enough attention at

227   the time. The European Union has also carried out numerous wind power hydrogen production

228   projects and has always been in a leading position in the use of wind power. They plan to

229   achieve sustainable development with full reliance on renewable energy by 2060. China

230   actively promotes cooperation between universities and enterprises in hydrogen production

231   from wind power, and successfully completed the hydrogen production station of the Hebei

232   Guyuan Hydrogen Production Project in 2017. This was China's first wind power hydrogen

233   production station and the largest hydrogen production station in the world at that time.

234   2.3   Fuel cell applications

235   Fuel cell is a device that directly converts chemical energy into electrical energy through

236   the reaction of fuel and oxygen. The products of the reaction are electricity and water.

237   Depending on the fuel used, some produce carbon dioxide and other emissions. The waste heat

238   of fuel cell is much less than that of direct fuel combustion, its energy conversion efficiency is

239   as high as 90%, and the heat recovery rate is as high as 30%-40% [40]. In addition, if hydrogen

240   is used as the fuel of the fuel cell, there will be no carbon dioxide in the reaction product, which

241   is more environmentally friendly. The fuel cell consists of a cathode, an anode and an electrolyte.

242   According to the different electrolytes used, common fuel cells can be divided into three types:

243   alkaline fuel cells (AFC), solid oxide fuel cells (SOFC) and proton exchange membrane fuel

244   cells (PEMFC) [41].

245   AFC was designed and published by Francis Thomas Bacon in 1959 and in the mid-1960s,

246   NASA began to use AFC to power the Apollo space program. Among these three technologies,

247   AFC has the advantages of low cost, simple and stable structure. It only needs to continuously

248   supply water at room temperature when the system is working. At present, AFC has been

249   developed relatively well [42], so it has been widely used in current commercial applications.

250   SOFC is highly efficient and it can use different kinds of fuels such as methanol and biogas

251   [43]. However, it usually needs to work in an environment above 500°C, this causes the

252   electrolysis system cannot start quickly and needs to overcome internal problems generated

253   under high temperature conditions. The current researches focus on the development of low

254   temperature, and increase the life of the system while reducing the cost of operation.

255   PEMFC has the advantages of low running temperature, low noise, high power density

256   and fast start-up [44]. PEMFC usually uses Pt as a reaction catalyst to increase the reaction rate

257   and gain more economic benefits [45]. The materials used in this technology are more easily

258   degradable and more environmentally friendly [46]. PRMFC has been used to replace automobile

259   engines and aero engines [47], but its cost is higher and its durability is poor, so it still needs

260   further research and improvement [48]. A large part of the high cost of PEMFC is due to the high

261   cost of Pt material and hydrogen supply [49]. Exploring how to use Pt alloys to replace pure Pt

262 is an important way to reduce costs. Using renewable energy to produce hydrogen and supply

263 PEMFC is also undoubtedly one of the important ways to reduce costs. Only by gradually

264 reducing the cost of use can the PEMFC technology have greater practical application prospects

265 and create greater commercial value.

266 As the cleanest energy source, hydrogen plays a vital role in reducing carbon dioxide

267 emissions and improving the current environment. The electrolysis of water to produce

268 hydrogen through electricity generated by solar and wind power is an important form of

269 collecting and storing these renewable energy sources. For ships and offshore platforms, the

270 use of hydrogen-oxygen fuel cells can effectively reduce EEDI and greatly optimize the energy

271 structure of offshore platforms. In addition, the use of hydrogen-oxygen fuel cell devices

272 instead of batteries as the energy storage device of the renewable energy power generation

273 system to solve the problem of intermittent can reduce the cost and make the system more

274 environmentally friendly.

275 Fuel cells and electrolyzers that use the same electrolyte generally follow the same

276 structure. The common methods for producing hydrogen by electrolysis mainly include

277 Alkaline water electrolysis (AWE), Solid oxide electrolysis (SOE) and Polymer electrolyte

278 membrane electrolysis (PEM). Table 2 shows the specific attributes and parameters.

279
<div align="center">Table 2 Details of different electrolysis</div>

	AWE [50]	SOE [51]	PEM [52]
Electrolyte	NAOH/KOH	ZrO2	Solid polymer
Cathode	Ni	LSM-YSZ,	C, Pt
Anode	Ni alloys	Ni-YSZ	C, Pt
Pressure / (bar)	2-10	<30	1-2
Temperature /(°C)	70-90	500-900	50-100
Capacity /	5-500 Nm^3 /h		20-40 kg/h

280 AWE has the longest development time and is the most complete method. Generally, Ni-

281 based metals are used as electrodes for AWE. The two electrodes are placed in an alkaline

282 solution and separated by a diaphragm. The system can operate between 20%-150% of the

283 design capacity. For solar and wind power generation systems with intermittent and large power

284 fluctuations, AWE has the advantages of low cost and system stability. The Utsira

285 wind/hydrogen demonstration plant installed a 600kW wind generator, using the AWE method

to produce hydrogen at the rate of 10Nm^3/h [53]. However, compared with other methods, the current density of AWE is not high, and the corrosive electrolyte used is not friendly to the environment and is prone to danger.

Solid oxide electrolysis (SOE) generally uses Ni-doped YSZ as the electrode material of the cathode and Lanthanum strontium manganate (LSM) as the electrode material of the anode. The hydrogen production method has the advantages of high efficiency, long life and high stability, but the electrolysis needs to be carried out at extremely high temperatures. At present, it is possible to consider using concentrated solar energy to provide a high-temperature environment for the reaction, and use other new energy technologies to provide electricity, so that renewable energy can be used throughout the reaction, which has better economic benefits.

The structure of the PEM system is simple, and the current density is higher, about four times that of AWE. PEM can accept dynamic energy, so it can be well used in solar and wind energy hydrogen production systems [54]. Table 3 shows some projects of PEM electrolysis hydrogen production around the world.

Table 3 PEM PROJECT

NAME	Time	Parameters	Source	Purpose
HYUNDER [55]	2008 to present	66 Nm^3/h; 300 bar	Wind power; PV	storage of renewable energy
Don Quichote [56]	2012-2018	30 Nm^3/h; 450 bar	Wind power; PV	Fuel hydrogen supply
levenmouth community energy project [57]	2016 to present	60 kW; 30bar	Wind power; PV	Store electricity; Fuel hydrogen supply
Pilot plant Falkenhagen [58]	2014 to present	2MW	PV	Store electricity
Lam Takhong wind hydrogen hybrid project [59]	2016 to present	1WM	Wind power	Store electricity

3. Renewable energy applications for ships

3.1 Solar for ship

The application of solar energy on ships firstly appeared in the last century. In 1997, Modular Mouldings manufactured the S B Collinda, which was the first solar ship to cross the English Channel. In October 2006, the Swiss 'Sun 21' all-solar powered ship completed the

feat of crossing the Atlantic Ocean. In November 2009, the world's first solar powered large-scale cargo ship "Auriga Leader" Vessel was successfully launched for sea trials with a PV of 40kW on board, including 328 solar panels. The electricity generated can meet 6.9% of the lighting requirements or 0.2% of the power requirements. PlanetSolar was launched on March 31, 2010, at a cost of up to 24 million dollars. It is 31 meters long, equipped with solar cells covering 537m^2 with the speed up to 10 knots. In May 2012, it completed the first trip around the world for solar-powered boat. MetaltecNaval's solar-powered commercial passenger ship EcoCat was launched in 2018. It can accommodate 120 passengers and its speed can reach up to 9 knots. The power of Solar boats is growing and their application has spread from small cruise ships to large cargo ship and ro-ro ships in just two decades.

In the past 20 years, the main problem of research has turned from how to simply use solar energy to ship platform to how to efficiently use solar PV system to provide stable power supply for ships. At present, the ship solar PV system is mainly divided into off-grid and grid-connected two types. The off-grid PV system is independent of the ship's power grid and relies on batteries to ensure a continuous supply of power. Its advantages include high security and simple system structure, the disadvantage is that the capacity of the battery needs to be several times the generation capacity of the PV system, in order to stable power output [60, 61]. The grid-connected PV system integrates the electricity generated by the solar system into the main power grid of the ship, therefore it does not have the above problems, and the electricity generated by the PV system can be more fully utilized. Its disadvantage is that the grid-connected system structure and principle is more complex, and for the safety of the power grid, the classification society stipulates that the capacity of the PV system shall not exceed 10% of the diesel generator. By comprehensively considering the actual situations, people still prefer to use the grid-connected system in most cases.

Sun et al. [62] proposed the basic principle of applying solar PV system to ship integrated power grid by analyzing the technical characteristics of off-grid and grid-connected ship PV systems. Combining off-grid and grid-connected PV systems, they designed and installed a hybrid PV system with battery storage for the 'COSCO TENGFEI'. The system can realize the flexible switching between off-grid and grid-connected operation modes according to the electric load and the state of charge of the battery, and operate stably under various modes. The

peak power of this solar PV system is up to 143kW saving 0.46 tons of fuel oil in one day and saving 40,000 dollars in one year [63].

ÇağlarKaratuğ et al. [64] designed a PV array layout for the ro-ro ship. The designed solar system can meet 7.38% of the ship's fuel demand. It provides 334.06 MWh of electricity to the ship's power grid within one year, reducing emissions by approximately 232.393 tons of CO_2 per year, 0.312 tons of SO_x and 3.942 tons of NOx. Yuan et al. [65] designed 135 PV panels in 'Anji204' with a total capacity of 37.12 kW. All the electricity generated is used to supply only the vehicle warehouse lighting system and living area lighting system on board the ship. PV system can generate about 45,000 kWh, reduce fuel consumption by about 16 tons, reduce CO_2 emissions by about 28.5 tons, SO_x about 0.63 tons, and NO_x about 0.05 tons every year.

After more and more solar modules are applied to ships, how to improve PV efficiency has become the focus of research. Zeńczak [66] proposed to increase the efficiency of the ship PV system by adding cooling modules. The PV system of ship ś Winoujście was renovated with the cooling modules, and the results of operation were analyzed. The results show that the method provided 17% more economic benefits for the ship than the PV module without cooling system.

Wen et al. [67] proposed a hybrid integrated method based on the random ship motion model to predict the optimal interval of onboard solar energy to reduce the impact of weather changes and ship position on the solar system and improve the efficiency of the solar system. A hybrid prediction model was formed by combining machine learning technology and particle swarm optimization (PSO), and it was actually tested on the power system on a large oil tanker. The results show that the system is very effective in improving the efficiency of the ship's solar energy system, and can be used as an important reference for the ship's energy management system. Divyajot [68] used variable inertia weight belt (TVIW) of the particle swarm optimization (PSO) method to study the PV, energy storage system on the tanker and diesel generator output between the mutual influence relationship, determining a proposed assembly PV module for the ship.

The application of solar PV technology on ships has matured, and the relevant operating strategies and efficiency improvement methods are the hot topics now. This is one of the most accessible renewable energy sources on ships, and it will also be an important method to

367 improve the energy structure of ships.

368 3.2 Wind for ship

369 Equipment of wind power occupies a lot of space, and it is difficult to use it in a ship with

370 a relatively compact space. Therefore, using different types of sails to provide auxiliary power

371 for the ship is one of the best ways for ships to use wind energy. A good wind assisted propulsion

372 device can reduce CO_2 emissions by up to 20% for ships [69], and save 1%-30% of fuel

373 consumption [70]. It is a very good improvement to ships for both the environment and the

374 economy.

375 At present, wind-assisted propulsion methods mainly include Rotors, Towing kites,

376 Suction wings and Rigid sails. Rotors usually refer to Flettner rotors. Fig.7 shows the basic

377 principles of Flettner rotors, which use the Magnus effect to generate thrust by installing

378 rotating cylindrical sails on the ship. Towing kites are mainly driven by the high-altitude sea

379 breeze, which hauls the ship forward. Suction wings are similar to airplane wings and achieve

380 upward lift through boundary layer suction. Current technologies such as Rigid sails, Soft sails,

381 and Hull sails are immature, and their practical applications are very limited. Among these

382 technologies, the most suitable one for large ships is the Flettner rotor in the Rotor sails.
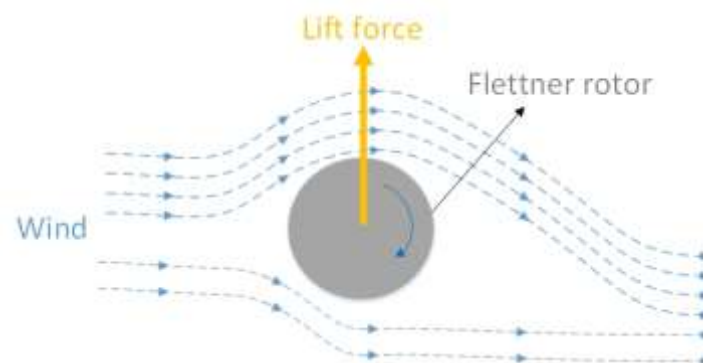
383

384 Fig 7 Flettner-rotor

385 Michael Traut et al. [71] concluded that towing kites can bring about 1%-2% power gains

386 of the main engine, and a single Flettner rotor can bring power benefit about 2-3%. In the

387 comparative analysis of multiple examples, the average power range of Flettner rotors mainly

388 ranges from 193 kW to 373 kW, and the average power range of Towing kites ranges from 127-

389 461kW. Flettner rotors can provide more power and are more stable than Towed kites, but kites

390 take up less deck space and are more economical.

391 Nader R. Ammar et al. [72] conducted a research on Flettner rotors for a bulk carrier. By

392   adding 4 Flettner rotors to it, they investigated the economic and environmental benefits of

393   three different routes. The results show that the average power of Flettner rotors is between 608

394   kW and 1,096 kW, which can reduce the fuel consumption by 8.5-16.2%.

395   Lu et al. [73] conducted a study on Flettner rotor technology for an oil tanker based on its

396   actual sailing data, and analyzed that using Flettner rotors can save 8.9% fuel consumption.

397   After analyzing the efficiency of Flettner rotors in different working conditions, it demonstrated

398   that the use of Flettner rotors is greatly affected by its ship type, speed, sailing route and

399   corresponding weather conditions. These factors must be comprehensively considered to select

400   the best Flettner rotor size and quantity.

401   Ibrahim et al. [74] took the bulk carrier between Damietta and Dunkirk as an example, and

402   studied the economic benefits with different paths and different sizes of Flettner rotors. The

403   research shows that the average output power of each rotor on the bulk carrier is 384 kW/h

404   under the best condition. The sum of the three rotors is equivalent to saving up to 22.28% fuel

405   consumption for bulk carrier, reducing NO_x and CO_2 emissions by 270.4 tons and 9272 tons

406   each year, bringing absolute benefits in both economic and environmental aspects.

407   Tillig et al. [75] proposed a ship performance model called ShipCLEAN to control the

408   Flettner rotor and analyze its impact on ships. The model was applied to an oil tanker and a ro-

409   ro ship, and it was analyzed and verified. The results showed that an oil tanker equipped with

410   6 Flettner rotors can save up to 30% fuel consumption, and the rolling of 4 Flettner rotors saved

411   14% fuel consumption.

412   Marcel et al. [76] developed an intelligent assistance system to enhance the capability of

413   wind-assisted ship propulsion, which can realize the operation of automatic optimization of the

414   energy system. Using a ship equipped with Flettner rotors as the experimental object. The data

415   acquisition, processing and storage modules in the system architecture were studied and

416   analyzed, and the system's human-machine interface (HMI) was used for visualization. It was

417   concluded that the system has the ability to optimize the working ability of the wind-assisted

418   ship propulsion system, which lays the foundation for further improving the fuel-saving ability

419   of wind-assisted ship propulsion.

420   3.3 Fuel cell for ship

421   Fuel cells show good energy properties such as low noise, low vibration, high efficiency

422 and environmentally friendly. It can be used as the main energy supply in various occasions. In

423 recent years, the research of fuel cell has gradually matured, and its practical application in

424 residences, ships, power plants and other places has also been further developed, which has

425 greatly stimulated people's research on using fuel cell systems for offshore platforms. At present,

426 most ships are powered by diesel generators. This method will produce a large amount of

427 greenhouse gases, nitrates and sulfides, which is not friendly to the environment. Using fuel

428 cells instead of diesel engines to supply electricity can not only reduce the emission of CO_2 and

429 gaseous pollutants, but also reduce the conversion of the primary energy form, thereby greatly

430 improving the efficiency of fuel utilization.

431 Fig 8 shows the working principle of the PEMFC system. PEMFC has high efficiency, fast

432 start-up, and the working temperature is easier to reach, and it can be used as the main power

433 supply energy for ships. In the 1970s, Germany developed the PEMFC system in military

434 equipment such as submarines [77]. However, because the PEMFC system needs to continuously

435 provide pure hydrogen as fuel, when the sailing time is too long, there will lack of hydrogen

436 supply. Therefore, if PEMFC is to be used on ships, a comprehensive and rigorous design of

437 hydrogen storage and replenishment scheme is required [78]. In the experiment near a

438 hydroelectric power plant, they installed two PEMFC systems with a power of 180kW on a ship

439 that can accommodate 200 people. The electricity produced by nearby hydroelectric power

440 plants is used to produce hydrogen, which solves the problem of the source of hydrogen and

441 also controls the production cost of hydrogen well. On the other hand, PEMFC does have the

442 disadvantages of high cost and low power generation. Further research and improvement on

443 power generation capacity and hydrogen production technology are needed for applying this

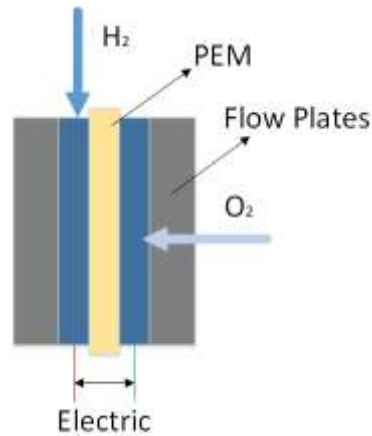444 technology to ships and increasing the economic benefits.

445

Fig 8. Working principle of PEMFC

447   Fig. 9 shows the working principle of SOFC. SOFC has relatively loose requirements on

448   fuel. In addition to using hydrogen, methane, biogas as energy supply, SOFC can even run by

449   diesel [79]. Therefore, SOFC is more flexible when it is put into practical application. At present,

450   there are many applications that put SOFC into the ship's power system. Facts have also proved

451   that the ship's power system using SOFC can achieve good economic benefits and is more

452   environmentally friendly.
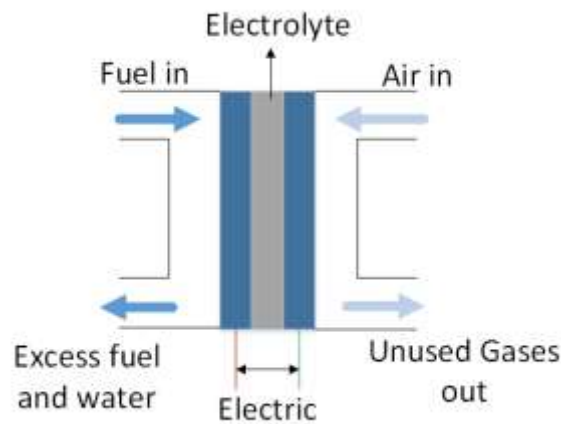

453

454   Fig 9. Working principle of SOFC

455   L.van Biert [80] proposed that the combination of SOFC and the current generator system

456   can achieve lower fuel consumption and has a better development prospect. FrancescoBaldi [81]

457   also proposed that SOFC ships using LNG can reduce greenhouse gas emissions by up to 34%,

458   which is one of the most effective ways to reduce greenhouse gas emissions.

459   Martinic et al. [82] used three 3700kW SOFC to replace the same power turbine generators

460   on LNG carriers. Analyzed and calculated the energy efficiency after replacement. The research

461   results show that after using the SOFC system, the power generation efficiency has increased

462   from the original 32.9% to 44.8%, and the energy utilization efficiency has been significantly

463   improved. Moreover, since the SOFC system generates a lot of heat, by reusing the waste heat

464   of the system, it is equivalent to saving 2.6% of natural gas consumption.

465   M. Díaz-de Baldasano [83] designed and installed two 250kW SOFC systems on the

466   platform supply vessel (PSV), using methanol to provide energy for the fuel cell, and

467   integrating the electrical energy generated by the fuel cell into the ship's power grid. The SOFC

468   system can provide up to 20% of the total energy supply for ships, and they also use the waste

469   heat of the SOFC system to produce hot water. The system greatly reduces the fuel consumption

470   of the ship and brings good economic benefits to the ship.

471   Rafiei [84] proposed to use fuel cells as the main power source for ships, using batteries to

472   cope with the problem of rapid load change, and constructed a zero-emission ferry structure.

473   According to the ship's own power generation and the shore power received when docking, the

474   scholar studied the specifications of the ship and the waterway, evaluated the energy limitations,

475   and optimized the energy management system. According to the ferry's daily route, the energy

476   management problem is implemented in the form of hourly average value, and the improved

477   sine cosine algorithm (ISCA) is used to obtain the best energy management mode for the ferry.

478   In general, the power generation capacity and volume of PEMFC are very suitable for ship

479   energy structure optimization. However, PEMFC requires pure hydrogen supply and the cost is

480   relatively high. The production of hydrogen through renewable energy will be one of the

481   important methods to reduce the price of hydrogen, which is also a problem that needs to be

482   solved urgently. SOFC can use more types of fuels and has greater power generation, so it is

483   also suitable for large ships such as oil tankers, container ships, or ships with long routes to

484   transform the energy structure. However, SOFC faces the problems of slow start-up and

485   excessively high operating temperature, which also need to be further researched and solved.

486   3.4 Shore power

487   There are more than 2,000 ports in the world, and 80% of global trade is carried out

488   through port transportation. The improvement of the energy structure during docking can

489   greatly improve the port environment and reduce the pollution caused by ships. During docking

490   at the port, the power of diesel generator of a container ship, bulk carrier and other ships is

491   between 2000-5000kW [85], while the power of diesel generator of cruise ships is greater, several

times that of ordinary ships. If sufficient shore power can be provided to ships during docking, the use of diesel generator can be reduced. The fuel consumption of ships can be greatly reduced. CO_2, SO_x and NO_x emissions can be greatly reduced and the port environment can be improved. Many ports in the world are actively promoting the use of shore power. Many container terminals in the United States and the United Kingdom have brought considerable environmental benefits through the use of shore power, which has promoted the development of shore power in many ports in Europe and North America [86]. Ports in China also use shore power. Since 2010, Lianyungang Port has used shore power to provide energy to cruise ships, and Shanghai Waigaoqiao Port has begun to provide shore power to moored ships. Since 2015, Dalian Port has renovated most of the container ship berths and began to provide shore power to container ships [97]. At present, nearly half of China's ports can provide shore power for docked ships.

For ports, the easiest way to increase shore power is to export it directly from the national grid. Although the operation is simple and the work is stable, it is still not environmentally friendly, which does not fundamentally change the pressure on the environment caused by the ship when it is docked. The use of renewable energy for shore power supply can solve this problem well. Solar PV can be well set up in the open area near the port, or even on the sea [88], to provide a large amount of energy for the shore power of the port. Wind farms near the port could also provide a large amount of energy to the port. Itiki et al. [89] proposed to use renewable energy such as solar energy and wind energy to build an offshore power generation system, and built a system framework that can provide power output to the coast. The power system they proposed can well provide renewable energy for shore power. Gutierrez-Romero [90] installed 163866.6 m^2 of solar panels in the port of Cartagena, Spain, and obtained a maximum of 1378.15 MWh of electricity per month, which can reduce a total of 10,000 tons of carbon emissions per year. It can be seen that the use of renewable energy to provide shore power to ships is very valuable.

4.   Hybrid energy system applications

PV is the most extensive renewable energy sources applied on ships. With the rapid development of technologies such as wind energy and fuel cells, there are more and more applications for assembling hybrid energy on ships. As early as June 2000, the "Solar Sailor"

522 ferry used combined solar and wind energy in the power supply of the propulsion system. Fuel
523 cells were used in military submarines in the early days. In 2003, Siemens created a hybrid
524 power system for the Navy that integrated fuel cells and diesel, and used it in submarines at
525 that time. The abundant solar and wind resources on the ocean are very conducive to the
526 development of renewable energy. Making full use of available resources is of great benefit to
527 the environment and shipowners. The comprehensive use of a variety of renewable energy
528 technologies on ships is conducive to further improving the energy structure of ships and
529 reducing fuel consumption and pollutant emissions. Moreover, a well-designed hybrid
530 renewable energy system can bring considerable economic benefits to the ship. Table 4 shows
531 the summary of research on hybrid renewable energy on ships in recent years.

532

Table 4 research on hybrid renewable energy on ships

	Basic information	Hybrid energy	Research content and results
Chen, Xi [91]	Diesel engine	PV system(210kW); Battery(432kWh); Diesel; onshore-power	Developed a new offshore HES optimized operation model using evolutionary algorithm, and significantly reduced the electricity cost of ships
Rafiei, Mehdi [84]	Ferry; Length 47m; Beam 10m; Average speed 11kn; electric propulsion	Fuel cell (700kW); Battery (400kW); cold-ironing	Transformed a conventional ferry into a zero-emission ship with renewable energy system. The economic benefits and feasibility were analyzed.
Guangmiao ZENG [92]	Length 332.95m; width	PV (210kW); Wind Turbines (1500kW);	The IABC algorithm was used to optimize the operation of the hybrid energy system. The influence of three

	60.00m; Diesel engine	Battery; Diesel Generator (1900kW)	different battery types on the system was compared, and the best configuration scheme was determined.
Tang, Ruoli[93]	Diesel engine	PV (210kW); Battery(432kWh); Diesel Generator (250kW); onshore-power	An optimal energy management model was established, and the dispatch method of model prediction and maximum power control was used to optimize the dispatch of the ship's power flow, and the optimal energy management plan was obtained.
Rui Yang[94]	Length 182.8m; width 32.2m; Speed 20.20kn; Deadweight 14759t; Diesel engine	PV (265 W); Battery(3.2V/100Ah); Diesel Generator (960 kW)	A multi-objective optimization model related to ship fuel economy and diesel generator efficiency is established, and the local group optimization algorithm is used to optimize the operation mode of the ship's power grid.
Tang, Ruoli[95]	Diesel engine	PV (210kW); Battery(432kWh); Diesel Generator (250kW); onshore-power	A power flow dispatching model for a hybrid system based on large-scale global optimization is proposed, which uses swarm intelligence to optimize the use of solar energy to minimize the cost of electricity for ships
Vahabzad, Neda[96]	Length 176.9m; width 28.6m; Diesel engine	Diesel generators (8500 kW); PV (1 MW); ESS (432kWh); cold-ironing	The economic analysis of the hybrid energy system is carried out, and the optimal energy dispatch of the hybrid marine power system is proposed.

Xuezhou Wang[97]	Length 19.5m; width 7.5m; Speed 22kn; electric propulsion	Diesel generators （2x720 kW）; Fuel cell(700kW); Battery(400kW)	The multi-objective double-layer optimization method is used to preliminarily optimize the size and energy management of the hybrid ship propulsion system.
Gaber, Mohab[98]	Diesel engine	PV （20kW）; Fuel cell （10kW）; Battery （40 Ah）	A hybrid energy system model was established, the corresponding energy management strategy was proposed, and the feasibility of the system was analyzed and studied.
ChaoukiGhenai[99]	Cruise ship; electric propulsion	PV(1200kW); PEM fuel Cell (1000kW); Diesel Generator(2×2760kW)	A theoretical model of a cruise ship hybrid renewable energy system is established, a simulation study is carried out on it, and an optimal control strategy for the hybrid energy system is proposed.
WannengYu[100]	Experimental test rig; Diesel engine	PV (30kW); Battery(50kWh); Diesel Generator (100 kW);	A solar hybrid energy experiment platform was built, an energy management monitoring system was developed, and the effectiveness and feasibility of the proposed control strategy were verified.
Mohsen Banaei[101]	Ferry Ship; electric propulsion	PV (10kW); Fuel cell (700kW); Battery(200kW); Cold-ironing(100kW)	A hybrid energy model for electric ferry was established, and an energy management strategy was proposed using the mixed integer linear programming method, and the effectiveness of the model was

			demonstrated through actual case studies.
Shuli Wen [102]	Length 332.95m; width 60.00m; Diesel engine	Wind Generator(30kW); PV (290kW); Diesel Generator(2MW); Battery.	A hybrid energy system is proposed, the system configuration is studied and analyzed, and the economic analysis of different configurations is carried out to determine the optimal configuration capacity of the system.

533

534 **5. Modeling and Analysis of HES**

535   For ships, there are nothing more than two operating states, either sailing at sea or berthing.

536 For these two states, we designed the corresponding comprehensive supply structure of

537 renewable energy, and carried out economic analysis and evaluation based on the parameters

538 in a large oil tanker reported in [102]. Fig. 10 shows the schematic diagram of the ship's

539 integrated energy system designed in this paper. In terms of power system, we design to carry

540 solar PV modules and fuel cell modules for ships. During the ship's voyage, the electricity

541 generated by the PV module is input into the ship's power grid, and together with the diesel

542 generator to supply the ship. In order to ensure the stable operation of the ship, the battery

543 module is equipped to reduce the impact of the power fluctuation of the PV module. Using fuel

544 cell as a backup power source equipped with a hydrogen storage tank, and the excess electricity

545 of the power generation system supply hydrogen electrolysis to produce hydrogen. In terms of

546 propulsion systems, installing Flettner rotors for auxiliary propulsion of ships can reduce a lot
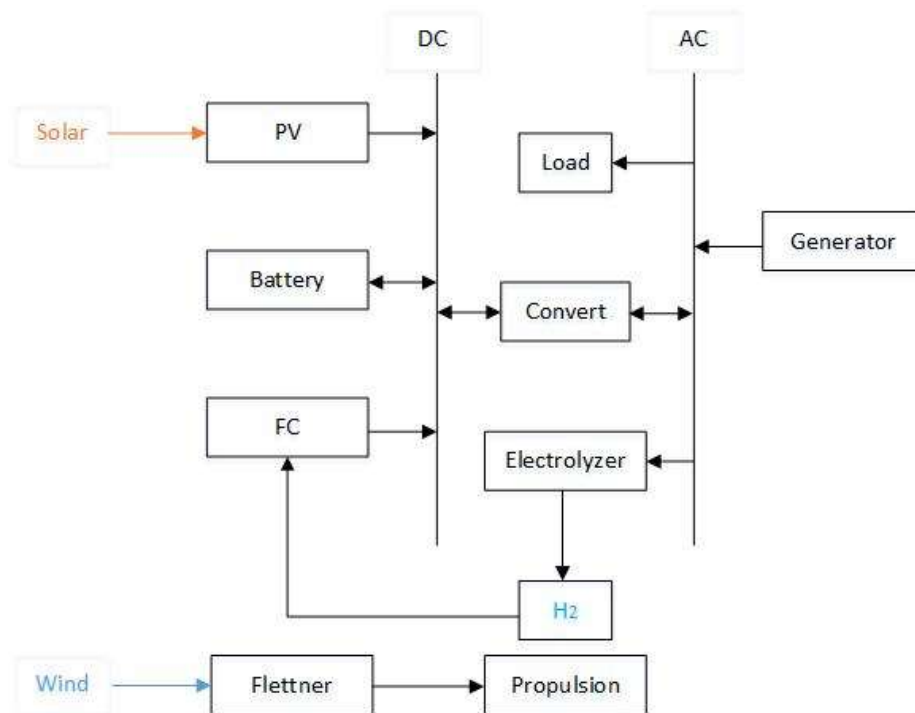
547 of fuel consumption and emissions.

548

549

550   Fig 10 hybrid energy system for ship

551   In another state, when the ship is in the port, the diesel generator stops working, and the

552   gird is connected to shore power. At this time, the ship uses the shore power as the main source

553   to supply the equipment to operate, and at the same time to charge the batteries. The PV module

554   continues to supply power at the same time as a power supplement. Fig 11 shows the working

555   principle of the hybrid renewable energy system for ports. For the port, in order to optimize its

556   energy structure, wind power plants can be set up nearby, so that the abundant wind resources

557   near the coast can be collected, and at the same time, the port can receive a large amount of

558   power source. According to the construction conditions around the port, the installation of solar

559   PV power plants can also provide a considerable part of the power resources for the port. When

560   wind power and solar power are sufficient, using the electricity to produce hydrogen by

561   electrolysis can provide a large amount of hydrogen supply for marine fuel cells.

562   The system is relatively complex and huge. This article focuses on the economic analysis

563   of the ship's hybrid energy system equipped with solar PV modules, diesel generator, fuel cell

564   and batteries. The analysis of fuel cell module and the wind-assisted propulsion module are
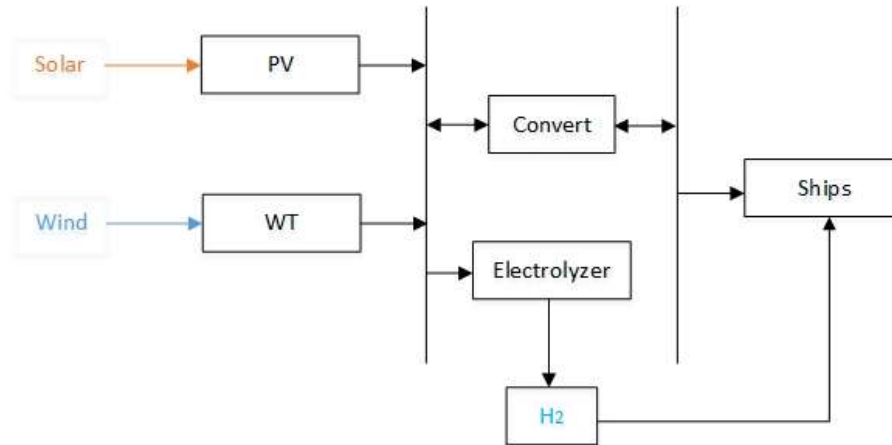
565   only briefly mentioned.

566

567 Fig 11 hybrid renewable energy system for ports

568 5.1 Basic information

569 The object of the Hybrid system is an oil tanker with the length of 330 m, width of 62 m

570 and weight of 100,000 tons. The load of the tanker under different working conditions is shown

571 in Table 5. The maximum load is 1790kW. Its sailing route is Qingdao, Shanghai, Hong Kong,

572 Singapore, Sri Lanka, Yemen and finally arrives in Egypt. The load is sorted according to its

573 actual working status. The sailing and freight tasks between Qingdao and Egypt are completed

574 in 25 days each month, and the remaining days at the end of the month dock in the port to rest.

575 The obtained operating load of the ship throughout the year is shown in Figure 12.

576

577 Table 5 The load of the tanker

Working status	Load power (kW)
Cruise	1580
Dock	1650
Loading and unloading	1290
Full speed	1790
Anchor	500

578

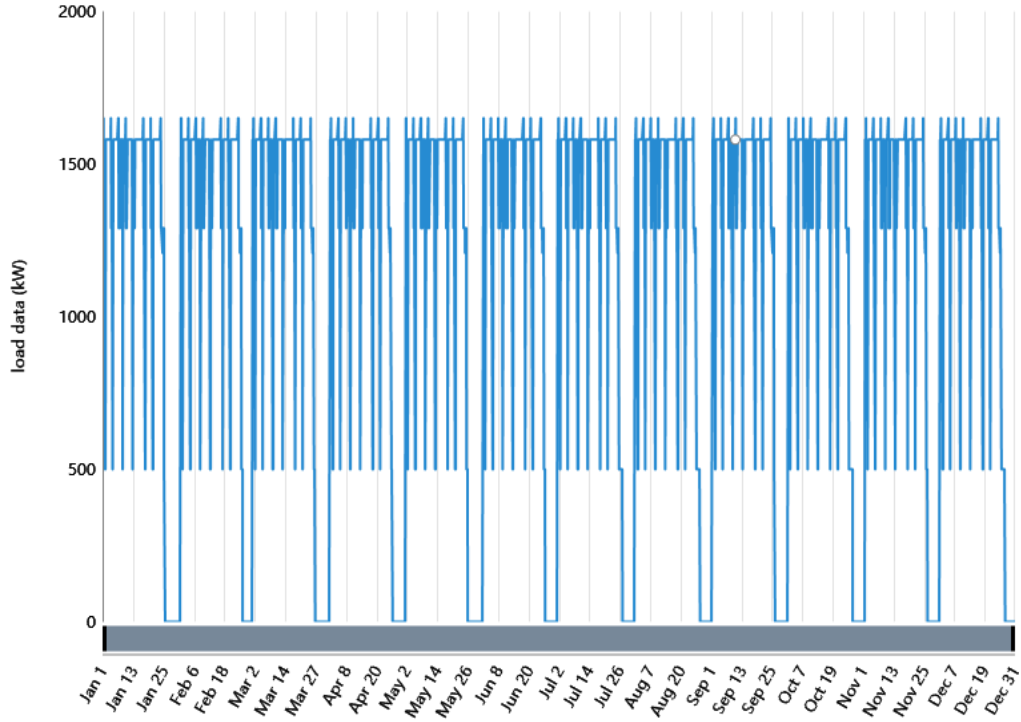579   Fig 12 Ship electrical load

580   Diesel generators must have the ability to independently supply power to the entire ship.

581   Choose 2000kW diesel generator as the main electrical power source considering the need to

582   leave at least 10% of the power generation margin. According to the requirements of China

583   Classification Society, the grid-connected PV capacity of ships should be less than 10% of

584   diesel generator sets [103], as a result, the capacity of selected PV module is 200kW. The power

585   generation status of the PV system is closely related to the solar radiation, so it is necessary to

586   accurately describe the solar radiation status of the ship [104-106]. According to the solar energy

587   data provided by NASA Prediction of worldwide energy resource, the amount of solar radiation

588   passing through the city is shown in Figure 13. The calculation method of the output power of

589   the PV module is as follows:

590
$$P = Y \cdot f \cdot \left(\frac{\overline{G}}{G_{stc}} \right) \left[1 + \alpha \left(T - T_{stc} \right) \right]$$

Where:

Y	= the rated capacity of the PV array, meaning its power output under standard test conditions [kW];
f	= the PV derating factor [%];
$\overline{G}$	= the solar radiation incident on the PV array in the current time step [kW/m²];

$\overline{G_{stc}}$ = the incident radiation at standard test conditions [1 kW/m²];

α = the temperature coefficient of power [%/°C];

T = the PV cell temperature in the current time step [°C];

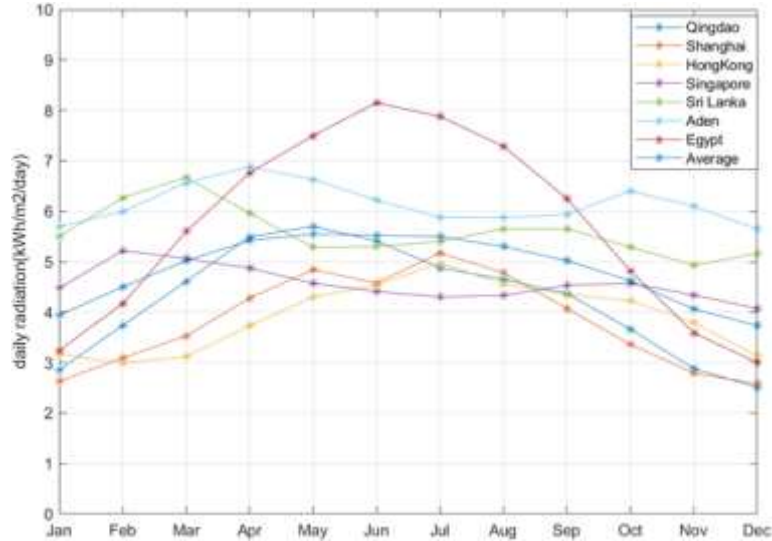T_{stc} = the PV cell temperature under standard test conditions [25°C]

Fig 13 solar radiation passing through the city

Use HOMER software to model and simulate the hybrid renewable energy power system studied in this paper. HOMER software was developed by the National Renewable Energy Laboratory (NREL) of the U.S. Department of Energy. It is used to construct complex hybrid energy power generation, energy storage and load management systems. It can reliably and efficiently analyze and optimize the energy structure of the ship's integrated system, and carry out economic analysis to provide the best system configuration plan for the ship. Select the main components of the energy system, including diesel generators, PV modules, batteries, and converters according to the ship load. The specific parameters are shown in Table 6. Figure 13 shows the structure of the built hybrid renewable energy power system.
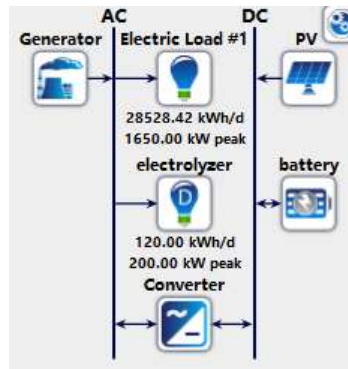

Fig 13 hybrid renewable energy power system

604		Table 6 parameters of main components		
	Generator	PV	Battery	Converter
Type	Generic Large Genset	Generic Flat plate	Li-Ion	System Converter
Rated power	2000 kW	200 kW	1kWh	1kW
Capital cost	300000 $	20000$	50$	300$
O& M cost	0.25 $/hour	10$/year	0	0
Life time	25000 hours	25 years	20 years	15 years
Derating factor	85%	85%		
Fuel type	Diesel			

605

606   5.2 Main system Result analysis

607   Changes in weather conditions have a greater impact on the photovoltaic system. It is

608   necessary to determine the power plan through the forecasted weather given the current weather

609   forecasting technology is well developed. The adjustment of the power system operation

610   strategy is very necessary. By using the Predictive dispatch strategy (PS) strategy, a more

611   reasonable power system operation strategy can be formulated by comprehensively considering

612   the upcoming load and energy supply situation. According to the basic information of the hybrid

613   renewable energy system, several system schemes with different configuration capacities that

614   can be operated reasonably are determined, and their hourly operating data is analyzed and

615   calculated to obtain the most economical system scheme.

616   After simulation calculations, the comparison results of different configurations are shown

617   in Figure 15. Under the premise that the diesel generator capacity and PV module capacity are

618   determined to be 2,000kW and 200kW respectively, the battery capacity that needs to be

619   installed is 220kWh, and the capacity of the converter is 114kW. In the results, the operating

620   conditions of the diesel engine for power generation are shown in Table 7. A total of 7,296 hours

621   of operation, fuel consumption of 2,687,266L, and power generation of 10,176,139kWh. The

622   PV system generated a total of 306,123 kWh during this operation. Figure 16 shows the specific

623   monthly average power generation of PV system and power generation diesel engines. It can

624   be seen that 97.1% of the power of the ship's power system is provided by diesel generator, and

625   PV modules provide 2.92% of the power.

626

627   Fig 15 The optimization result of HRE system components.

628   Table 7 Generator date

Parameters	Value
Hours	7,296
Production (kWh)	10,176,139
Fuel (L)	2,687,266
O&M cost ($/year)	1,824
Fuel cost ($/year)	1,343,633

629

630   Fig 16 The monthly average power generation

631   Figure 17 shows the specific operation of the ship's power system, including the total load

632   used for ship operation and the idle load used for hydrogen production by electrolysis, as well

633   as the power supplied by diesel generators, PV modules, and batteries. It can be seen that the

634 electrical load of ships mainly relies on diesel generator, which ensures the safety and stability

635 of the power grid. Solar PV power is greatly affected by the environment, but the addition of

636 batteries effectively reduces the volatility of auxiliary power supply, and overall provides a

637 considerable amount of power input for the ship's power grid. By supplying the electrolysis

638 device with the electricity during idle time, the utilization rate of energy is effectively increased,

639 and the hydrogen produced has high economic value, which can provide a certain supply for

640 the fuel cell part.

641

642

643 Fig 17 Ship electrical system operation status

644   Figure 18 shows the economic evaluation results of the system，including The Return

645 on Investment (ROI) and Simple payback. HOMER reflects the economic benefits of the new

646 energy system by comparing with the initial system that only relies on diesel generators to

647 supply electricity. ROI is the annual cost savings relative to the initial investment and is

648 calculated as follows:

$$ROI = \frac{\sum_{i=0}^{R_{proj}} C_{i,ref} - C_i}{R_{proj}(C_{cap} - C_{cap,ref})}$$

649

  Where:

        $C_{i,ref}$ = nominal annual cash flow for base system;

$$C_i \quad = \text{nominal annual cash flow for current system;}$$

$$R_{proj} \quad = \text{project lifetime in years;}$$

$$C_{cap} \quad = \text{capital cost of the current system;}$$

$$C_{cap,ref} \quad = \text{capital cost of the base system.}$$

Economic Metrics

IRR ⓘ	44%
ROI ⓘ	39%
Simple Payback ⓘ	2.3 yr

Fig 18 Economic Metrics

The simple payback period refers to the number of years for the cumulative cash flow between the current system and the basic case system to change from negative to positive, that is, how long it takes to recover the investment cost difference between the current system and the basic case system. From the analysis results, it can be concluded that the proposed system can save 39% of the initial investment each year, and achieve the same capital consumption as the initial basic system when the system runs for 2.3 years, filling the additional cost of the proposed system.

Figure 19 shows the comparison of capital consumption between the proposed system and the basic system. Net present costs (NPC) means the total cost of installing and operating the entire life cycle minus all the income it obtains during the project life cycle. The costs in this system mainly include infrastructure costs, replacement costs, operation costs, maintenance costs and fuel cost. After analysis and calculation, the proposed system can save 200k USD. Initial capital is the total cost of the installation of the proposed system, which is USD 365,310. which is 65,310 USD more than the basic system for the construction of renewable energy modules. Among them, 65,310 USD more than the basic system is the construction funds for renewable energy modules. O&M represents the operating and maintenance costs of the system. The addition of a renewable energy system can improve the daily operating status of the ship's power grid and power generation diesel engines. At the same time, the optimization of the

670　operation and maintenance strategy can also reduce the loss of equipment, so the system's

671　operation and maintenance costs tend to reduce.

Cost Summary

	Base Case	Lowest Cost System
NPC ⓘ	$11.7M	$11.5M
Initial Capital	$300,000	$365,310
O&M ⓘ	$1.45M/yr	$1.42M/yr
LCOE ⓘ	$0.143/kWh	$0.141/kWh

672

673　Fig 19 Cost Summary

674　　The levelized cost of energy (LCOE) is the average cost required for the system to generate

675　useful electricity per kWh. The LCOE value of the proposed system is 0.141$/kWh, which less

676　than the LCOE of the basic system by 1.4%. It means proposed system gets good economic

677　benefits and is of great significance for improving the energy structure of ships and protecting

678　the environment. The calculation formula of LCOE is as follows:

679
$$LCOE = \frac{C_{ann,tot}}{E_{served}}$$

　Where

　　　$C_{ann,tot}$　= total annualized cost of the system ($/year);

　　　E_{served}　= total electrical load served (kWh/year).

680

681　　Table 8 shows the comparison results of ship emissions. After installing the PV module,

682　the new system can reduce emissions of 151,467 kg of CO_2, 370 kg of SO_X, 150 kg of NO_X and

683　a large amount of other harmful gases each year, which greatly improves the environmental

684　performance of the ship and has an important impact on improving the ship exhaust emissions.

685

686

687

688

$$\left(\prod_{j=1}^{n}f_{j}\right)\left(\sum_{i=1}^{nME}P_{ME(i)}\cdot C_{FME(i)}\cdot SFC_{ME(i)}\right)+\left(P_{AE}\cdot C_{FAE}\cdot SFC_{AE}*\right)+\left(\left(\prod_{j=1}^{n}f_{j}\cdot\sum_{i=1}^{nPTI}P_{PTI(i)}-\sum_{i=1}^{neff}f_{eff(i)}\cdot P_{AEeff(i)}\right)C_{FAE}\cdot SFC_{AE}\right)-\left(\sum_{i=1}^{neff}f_{eff(i)}\cdot P_{eff(i)}\cdot C_{FME}\cdot SFC_{ME}\right)$$

Table 8 Emission

Emission(kg/year)	Based case	Lowest cost system	Reduction
CO2	7198084	7046617	151467
SOX	17595	17225	370
NOX	7137	6987	150
CO1	37239	36455	784
Particulate Matter	318	312	6
Unburned Hydrocarbons	1976	1935	41

690

691 The Energy Efficiency Design Index (EEDI) is a measurement tool that characterizes the

692 inherent CO_2 emission levels of ships in the design and construction phases. Renewable energy

693 transformation of ship energy systems is beneficial to reduce ships' performance. Increasing

694 renewable energy is conducive to improving the ship's energy system and effectively reducing

695 the EEDI. Reference EEDI is a standard and the EEDI calculated according to the actual

696 situation of the ship needs to be less than the Reference EEDI. The calculation formula of

697 Reference EEDI is as follows:

698 $$Reference\ EEDI = a \times b^{-c}$$

For tankers:

a = 1218.8;

b = Ship capacity;

C = 0.488.

699

700 After calculation, the Reference EEDI of the research object is 4.425 $g \cdot CO_2/ton \cdot mile$,

701 that is, for the current tanker, it needs to meet the value less than 4.425 to meet the requirements.

702 In order to explore the improvement of the energy structure by the proposed system in this

703 paper, the superiority of the system is reflected by calculating the reduced EEDI value of the

704 ship. The calculation formula of EEDI is as follows:

705 $$EEDI = \frac{\left(\prod_{j=1}^{n}f_{j}\right)\left(\sum_{i=1}^{nME}P_{ME(i)}\cdot C_{FME(i)}\cdot SFC_{ME(i)}\right)+\left(P_{AE}\cdot C_{FAE}\cdot SFC_{AE}*\right)+\left(\left(\prod_{j=1}^{n}f_{j}\cdot\sum_{i=1}^{nPTI}P_{PTI(i)}-\sum_{i=1}^{neff}f_{eff(i)}\cdot P_{AEeff(i)}\right)C_{FAE}\cdot SFC_{AE}\right)-\left(\sum_{i=1}^{neff}f_{eff(i)}\cdot P_{eff(i)}\cdot C_{FME}\cdot SFC_{ME}\right)}{f_{i}\cdot f_{c}\cdot capacity \cdot V_{ref}\cdot f_{w}}$$

706 Analyzing the content of the formula, it is concluded that the numerator of the EEDI
707 calculation formula represents the source of CO2 emitted by the ship and the reason for
708 reducing emissions. It is mainly composed of five parts: main engine propulsion fuel
709 consumption, auxiliary engine daily fuel consumption, shaft generator, and innovative
710 technology reduction. Power consumption and fuel consumption reduced by innovative
711 technology. The denominator represents the shipping capacity of the ship, mainly including
712 loading capacity and speed. This article aims at the impact of increased PV modules on ships,
713 and analyzes the reduced EEDI value. The calculation formula of ΔEEDI is as follows:

714
$$\Box EEDI = \frac{\sum_{i=1}^{neff} f_{eff(i)} \cdot P_{AEeff(i)} \cdot C_{FAE} \cdot SFC_{AE}}{f_i \cdot f_c \cdot capacity \cdot V_{ref} \cdot f_w}$$

Where:

$f_{eff(i)}$: The ratio of average PV power generation in main global shipping routes to the nominal PV power generation specified by the manufacturer.

$P_{AEeff(i)}$: The required auxiliary engine power to supply normal maximum sea load and includes necessary power for propulsion machinery/systems and accommodation.

$f_{eff(i)} \cdot P_{AEeff(i)}$: The total net electric power (kW) generated by the PV power generation system [107].

C_{FAE} : The nondimensional conversion factor between fuel consumption and CO2 emission.

SFC_{AE} : Certified-specific fuel consumption.

f_i : The capacity correction factor.

f_c : The cubic capacity correction factor.

$capacity$: DWT at maximum summer load draft as certified in the vessel stability booklet approved by the Administration for tankers.

V_{ref} :   The ship speed measured in knots.

f_w :   Weather factor, accounts for a decrease in speed in representative sea conditions of wave height, wave frequency.

715

716   The value of each parameter is shown in Table 9 by consulting relevant specifications.

717   After calculation the proposed system can reduce $\Delta EEDI = 0.0888 \text{ g} \cdot CO_2/\text{ton} \cdot \text{mile}$ for the ship.

718   tanker construction generally takes the Reference EEDI as the standard, and a slight reduction

719   will bring a large amount of capital investment. Therefore, the actual EEDI of the tanker is

720   generally very close to Reference EEDI. The calculated value of $\Delta EEDI$ is equivalent to 2.0%

721   of the oil tanker construction standard (4.425 g CO2/ton mile), which has achieved a very good

722   improved effect for large ocean-going ships, which can effectively improve the energy structure

723   of the tanker and reduce a large amount of CO2 emissions.

724   Table 9 Values of EEDI calculation parameters

Parameters	Values
$f_{eff(i)} \cdot P_{AEeff(i)}$	200
C_{FAE}	3.026
SFC_{AE}	220
f_i	1
f_c	1
f_w	1

725

726   5.3 Other proposals

727   The proposed system described includes the use of electrolyzers to produce hydrogen

728   supplying fuel cells, Flettner rotor wind assisted propulsion, and the improvement of the shore

729   power structure of renewable energy. The following is only a brief description to provide ideas

730   and initial structure ideas for the next work.

731   In the proposed system, we used an electrolysis hydrogen production device that runs on

732   idle time. Figure 20 shows the operation of the device within one year. The hydrogen production

733   capacity of the electrolysis device is 40kWh/kg, which can electrolyze 1,000kg of hydrogen in

734   a year. Since it is very uneconomical to supply fuel cells to generate electricity after electrolysis

735   on ships, fuel cells are only used in special circumstances. PEMFC has no requirements for

736   operating temperature and can meet the requirements of fast start-up of the power system,

737   providing 25,000kWh of flexible and efficient power supply for the ship every year. Moreover,

738   for electric propulsion ships, when fuel cells are used as one of the main power sources, the

739   transformation scheme described in this article will have a good redundant electric energy

740   recovery benefit.

741

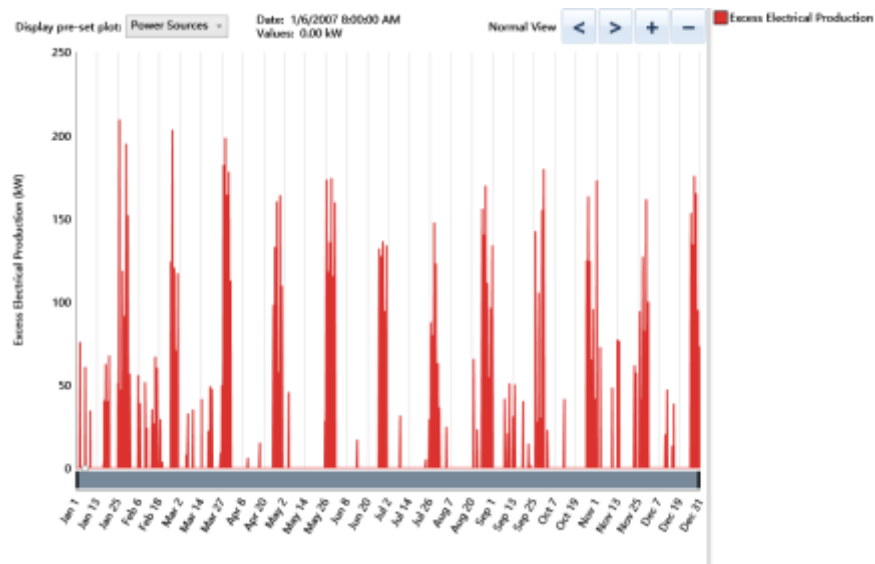742   Fig 20 Operation status of electrolysis device

743   For large ocean-going ships, the installation of Flettner rotors is an important method to

744   reduce the fuel consumption of the main engine. After researching and collating relevant

745   literature, it is found that each Flettner rotor can generally reduce the fuel consumption of ships

746   by 2%-8.9%. Installing four Flettner rotors for the tanker described in this article can

747   theoretically reduce the fuel consumption of the ship by 8%-35.6%. This is of great significance

748   for reducing ship operating costs and reducing pollutant emissions.

749   The ship described in this article stays in the port nearly 14% of the time throughout the

750   year, and its electrical load during loading and unloading is as high as 1290kW, which is only

751   290kW less than during normal voyages. If shore power is used to power ships in this state, a

752 lot of fuel consumption can be saved. In addition, if the shore power is consisted of renewable

753 energy, large-scale solar and wind farms are built around the port, and solar power is combined

754 with wind power to build an overall renewable energy system, which can greatly improve the

755 energy structure of the port. It is also possible to construct an electric hydrogen production plant

756 near the port to produce hydrogen from the excess electric energy when the load is small, and

757 to provide hydrogen for ships equipped with hydrogen-oxygen fuel cells, which can make the

758 ship and shore power more environmentally friendly. This proposal has a great impact on

759 improving the energy structure of the shipping industry.

760 **6. Conclusions**

761 The shipping industry is currently facing increasingly stringent laws and regulations, and

762 the standards for energy consumption and pollution of ships are getting higher and higher.

763 Coupled with the sluggish development of the shipping industry worldwide, the survival of the

764 traditional shipping industry has become more and more distressed. Under this circumstance,

765 renewable energy technologies have gradually matured, bringing important opportunities to the

766 shipping industry. Using renewable energy technologies such as solar, wind and fuel cells to

767 optimize the energy structure of ships has become one of the main ways for the current ship

768 industry to reduce the emissions and pressure on the natural environment. At the same time, a

769 well-designed new energy system can also reduce a considerable part of long-term operating

770 costs for ships, and has very good economic benefits.

771 This article summarizes the development and research status of solar energy, wind energy,

772 and fuel cell, focusing on their application and research in the ship industry. A hybrid solar/wind

773 energy/fuel cell ship power system model is constructed for ships, and a hybrid solar/wind

774 energy power supply and hydrogen production model is proposed for port shore power. The

775 simulation analysis is used to optimize the design of the renewable power system, focusing on

776 the emission reduction and economic benefits brought by solar photovoltaic to the ship. The

777 results show that the proposed hybrid renewable energy system can reduce emissions of

778 151,467 kg of CO_2, 370 kg of SO_X, 150 kg of NO_X and a large amount of other harmful gases

779 for 10W-ton tankers every year. Through calculation, the proposed system can also reduce the

780 EEDI value by 2.0%, and has achieved good performance in environmental protection. In

781 addition, the system can provide 2.92% of the electricity for 10W-ton tankers every year, with

a payback period of only 2.3 years, which brings good economic benefits to ships.

The future plan will continue modifying the proposed hybrid power model and determine best balance between different energy sources. The operation mode calculation under shore power state will be performed to investigate the whole process economics of the ship sailing and landing. Experimental validation on the modified calculation model will also be carried out.

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